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REMARKS/ARGUMENTS

The Examiner is maintaining the rejection of the claims primarily over Kobayashi et al. alone or in combination with other references. There is also a rejection of claims 17-22 and 27 over Ichinose; and a double patenting rejection over US 6,582,802 to Ohbayashi et al. of claims 17 and 20.

The Examiner's rejections are based on the Examiner's interpretation of the meaning of the claims in view of the Examiner's misunderstanding of the term "constant drying rate period." "falling drying rate period." Upon review of the Examiner's comments applicants realize that the figure showing the rate of total moisture content and the temperature of the target material was misunderstood. This is, in part, because the temperature of the target material, as shown in the figure, rises during the "falling drying rate period," as explained in the specification (see discussion below). In any case, it is requested that the Examiner reconsider all of the rejections, including the double-patenting rejection, in view of the following further explanation concerning the "constant" and "falling" drying rate period as explained below.

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I. Explanation of the Meaning of "Constant" and "Falling" Drying
   Rate Periods for the Present Invention

Annexed hereto are two figures to help illustrate the

intended meaning of the terms in question. Fig. A is the same

figure previously presented. Fig. B is a new figure showing the

rate at which moisture is vaporized.

"A constant drying rate period" is one wherein the same

amount of moisture which vaporizes per unit of time in the period

is constant. Therefore, the rate at which the total moisture

content falls is shown as a constant rate in Fig. A (II). As far

as a temperature of target material is concerned, the temperature

of the material remains essentially constant because the heat of

vaporization of the solvent in the period (II) is the controlling

factor. In other words, since the solvent is essentially free,

the temperature of the material is controlled by the evaporation

of the solvent (heat of vaporization to evaporate the solvent

keeps the temperatures from rising).

"A falling drying rate period" is one in which the amount of

vaporized moisture reduces in the period. Since the free solvent

has been driven off in the earlier period, the total moisture

content is relatively small and tied up in the material.

Therefore, as a practical matter, for the drying of the present

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invention, the amount of total moisture content does not greatly
change as shown in the Fig. A (III). Without the vaporization of
the solvent, the temperature of the material goes up because the
material is heated and heat of vaporization does not absorb the
heat, in the falling drying rate period (III).

II.   Support in the Specification for the Meaning of "Constant"
      and "Falling" Drying Rate

     Even if the art could interpret the terms differently, the
specification defines the terms.   Attention is directed
especially to the disclosure in the specification at page 21 et
seq. which discusses the drying process.   Attention is directed
especially to the discussion in the last paragraph on page 21
through the second paragraph on page 22.   As described on page 21
starting in line 10, the constant drying rate period occurs when
the ink-jet recording sheet comprises a relatively large amount
of water and solvents during the initial drying period.   The
surface temperature of the side having the porous layer is kept
almost constant due to the fact that relatively free water and
solvents evaporate while deriving those of latent heat
vaporization.   The constant temperature period is called the
constant drying rate.

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The discussion on page 21 continues to discuss the period when water and solvents, which interact with the hydrophilic binders, are evaporated. It is explained that, since there is no free solvent evaporation, the temperature increases (to provide energy to release any interaction between the solvent and the hydrophilic binders). As explained in the first few lines on page 22, the evaporation rate of water from the surface is greater than the movement of water in the coating layer. It is during this falling drying rate period in which void formation starts.

In view of the above and the further discussions concerning methods of confirming the drying rates, etc. which follow in the specification, applicants submit that the meaning of the "constant drying rate period" and the "falling drying rate period" as previously discussed and as explained above, is fully supported by the specification as originally filed.

III. Art Publications Support Applicants' Position

The Examiner appears to consider that applicants position with respect to the meaning of these terms is contrary to the meaning known to one of ordinary skill in the art (bottom of page 8 and beginning of page 9 of the Office Action). Therefore,

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the Examiner considers that applicants' arguments are at odds

with the conventional meanings of the phrases. The Examiner did

not provide any publications for consideration by applicants

showing the Examiner's position. However, annexed hereto is a

publication "Modelling the Drying of Solvent Coatings on

Continuous Webs," which is consistent with applicants' intended

meaning. In particular, referring to the summary on page 1, in

the second paragraph, the second sentence states

> "When the diffusion of solvent to the surface
> is found to be less than the drying rate in
> the constant rate period, then constant rate
> drying is over and falling rate drying
> begins."

Also, on page 3 in the second paragraph, there is a similar

explanation as to when the falling rate begins as noted above in

the discussion of the present specification disclosure. These

definitions are essentially the same as the ones applicants

consider appropriate and disclosed in applicants' specification.
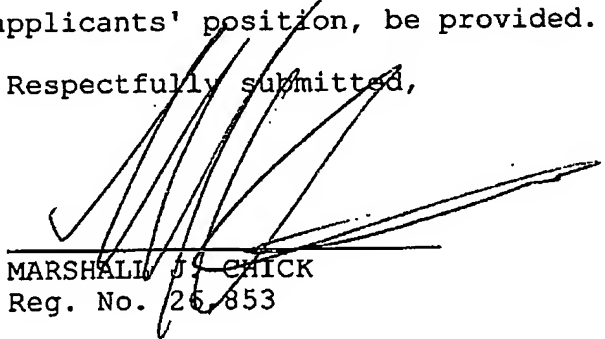
In view of the above, it is requested that the previous

arguments distinguishing over the art be reconsidered as being

fully supported by the present specification and the usual

knowledge in the art, and that the rejections be withdrawn and a

favorable action on the merits be provided. Also,

reconsideration of the double-patenting rejection is requested.

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If the Examiner is maintaining the rejections on the basis that applicants are using terminology which is inconsistent with the usual terminology in the art, it is requested that some evidence be provided of this usual terminology and also it is requested that an explanation as to why applicants' specification is not sufficient to support applicants' position, be provided.

Respectfully submitted,

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Encls.   Figures A and B

        Publication entitled: "Modelling the Drying of Solvent
                               Coatings on Continuous Webs"

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Fig. A

Rate of total moisture content

(III)

(II)

(I)

Temperature   of   target
material

Time

(I) a preheating period
(II) a constant drying rate period
(III) a falling drying rate period

Fig. B

(I)

(II)

(III)

Rate of vaporized moisture

Time

(I) a preheating period
(II) a constant drying rate period
(III) a falling drying rate period
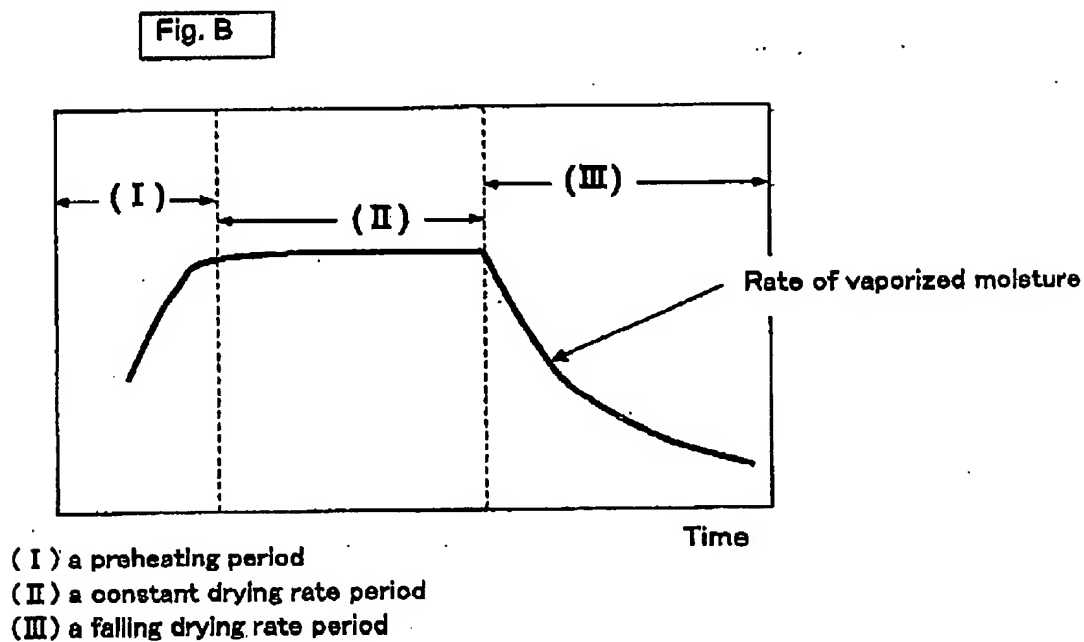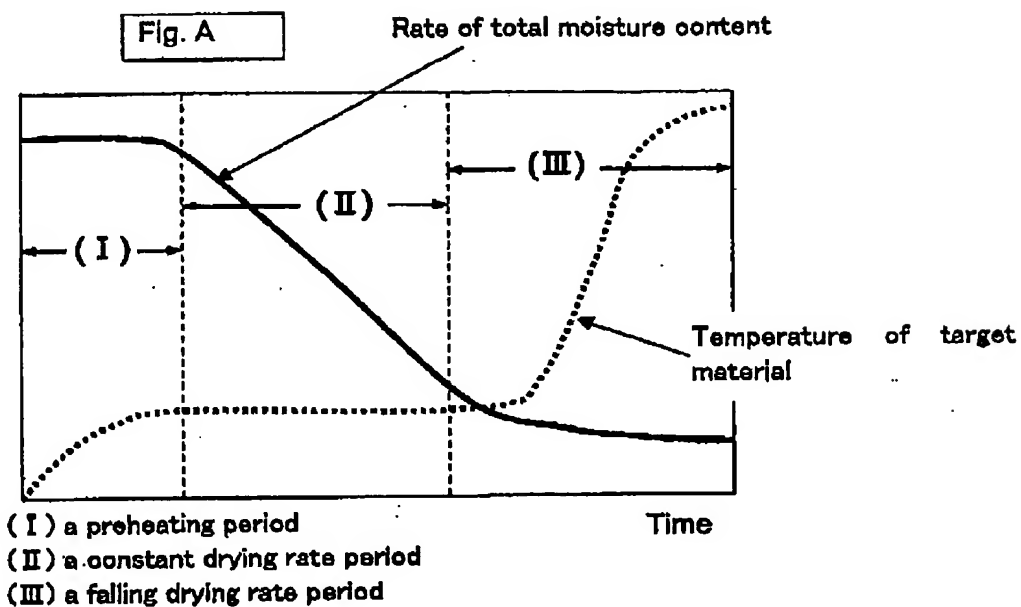
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MODELLING THE DRYING OF

SOLVENT COATINGS ON CONTINUOUS WEBS

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SUMMARY

The drying of solvent coatings on continuous webs has been modeled using a spreadsheet in Lotus 1-2-3 v. 3. The dryer may have up to seven drying zones where the air temperatures, air velocities, and solvent concentrations in the air can be varied independently. The web is assumed to be impervious, with evaporation of the solvent from one side only, but the drying can be either single-sided or double-sided. The solvent can consist of up to three components. The data base in the spreadsheet now contains 14 solvents, and more can be easily added. The Wilson equation is used to account for non-ideality of the solvent mixtures. Wilson constants for 44 solvent pairs are presently in the data base.

The model calculates the rates of evaporation in the constant rate period and in the falling rate period. When the diffusion of solvent to the surface is found to be less than the drying rate in the constant rate period, then constant rate drying is over and falling rate drying begins.

The heat transfer coefficient at air velocity or plenum pressure must be known or estimated. It is then calculated for the particular zone conditions. The web temperatures during the constant rate period are found using the equations of Cary and Gutoff[1]. A factor used to correct for the reduction of the vapor pressure due to dissolved species can be varied to give the correct web temperature in a test run.

The solvent diffusivity in the coating is a function of temperature and of solvent concentration, and a three-constant equation based on free volume theory is used to estimate it. One constant is the activation energy, and that is taken as a value typical for diffusion, about 15,000 J/mol (3582 cal/mol). Changing it slightly seems to have little effect. The other two constants are varied to make the model match a test run. These two constants do not seem to be independent and actually only one needs to be varied.

The coating is divided into a number of slices, usually ten, in which the solvent concentrations and the diffusivities are calculated. The drying rate in the falling rate period is equal to the rate of diffusion to the surface.

When drying air is recirculated the solvent level in the drying air can be calculated by a material balance. Otherwise the program assumes that the incoming air has no solvent. The concentration of solvent at the surface is assumed to be zero, as if the air has no solvent. If the air contains solvent then an equilibrium relationship ought to be introduced, but this relationship is often unknown and is therefore often neglected. This relationship could be similar to a published one giving the concentration of water in gelatin in equilibrium with air as a function of relative humidity and temperature.

The spreadsheet consists of four worksheets. Input data is entered on sheet A, the calculations are carried out on sheet B, sheet C contains the solvent data base and calculates

the average solvent properties, and the macros are on sheet D. To start the calculations one hits Alternate-A. To change the solvent one hits Alternate-Q. A copy of most of sheet A is printed out with the temperatures and solvent levels at the end of each zone and also the location of the end of the constant rate period. Two graphs, one linear and one semi-logarithmic showing the temperatures and solvent levels throughout the dryer, are also printed out.

THE MODEL

Modelling of solvent drying is divided into three steps:

- the constant rate period

- the transition between the constant and falling rate periods

- the falling rate period, and

In addition, the heat transfer coefficient at a reference condition must be known. All of the modelling, while in principle relatively straight forward, involves a number of assumptions which should be explicitly stated. And the modelling for both drying periods must be tested to validate the model and to fit constants and correction factors to the model. The constants that need to be found are:

- the heat transfer coefficient at a reference air velocity or plenum pressure.

- the constants in the diffusivity equation.

- the vapor pressure factor.

With aqueous coatings almost all the drying takes place in the constant rate period, and a model just describing the constant rate drying is adequate for many purposes. Such a model was developed by Cary and Gutoff (1991). With solvent coatings most of the drying occurs in the falling rate period; in some cases the constant rate period os over before the coating enters the dryer.

In the constant rate period the wet coating behaves as if it were a pool of solvent. While the "pool" remains a "pool" the evaporation rate will remain constant. The rate of evaporation from the "pool" of solvent will depend only on the temperature of the solvent and on the conditions of the drying air; the rate of flow of the solvent to the surface of the coating plays no role at all. In single-sided drying the temperature of the coating will remain constant at the wet bulb temperature of the air with respect to the particular solvent. In double-sided drying the temperature will be higher. The rate of drying can be found from the rate of heat transfer from the air to the coating divided by the heat of vaporization of the solvent. Modelling the drying mainly involves determining the web temperature. With

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thin coatings on relatively thin webs the temperature will be quite uniform (within a degree or two) between the surface of the coating and the bottom of the web, except for a fraction of a second after conditions, such as air temperatures, change. This assumption of temperature uniformity gives us the lumped-parameter model.

At the end of the constant rate period dry patches will appear on the surface of the coating and the rate of heat removal by evaporation will no longer equal the rate of heat transfer from the air to the coated web. The diffusion of solvent by diffusion to the surface by is no longer adequate to keep the surface of the coating wet, the rate of drying decreases, and the falling rate period begins. The web temperature increases, rising to the temperature of the drying air. When all of the surface appears dry the rate of drying is controlled only by the rate of diffusion to the surface.

[With porous webs, such as uncoated papers, and with porous coatings, such as clay coatings with low binder levels, mechanisms other than diffusion will control the evaporation rate during falling rate drying. This model only concerns diffusion.]

HEAT TRANSFER COEFFICIENT

Before any modelling is done the heat transfer coefficient at a reference plenum pressure or reference velocity must be known or measured. It is difficult to calculate the heat transfer coefficient, although Martin[1] does give a method for doing this. However, one can calculate the heat transfer coefficient from the temperature profile in the dryer of an uncoated dry web. This is based on an unsteady state heat balance on the web. If a section of the uncoated web is heated by hot air from both sides, then the rate of accumulation of energy in the web is equal to the rate energy flows into the web. No energy flows out of the web. Thus, following a unit area of web in the dryer gives

$$h_w \, \rho \, c_p \frac{dT}{d\theta} = (h_{ctg} + h_{base}) \, (T_a - T_w)$$

$$\int_{T_{v,o}}^{T_v} \frac{dT_w}{(T_a - T_w)} = \frac{(h_{ctg} + h_{base})}{h_w \, \rho \, c_p} \int_0^\theta d\theta$$

$$h_{ctg} + h_{base} = \frac{h_w \, \rho \, c_p}{\theta} \ln\left(\frac{T_a - T_{v,o}}{T_a - T_v}\right) \tag{1}$$

where h_{base} = heat transfer coefficient, back side   W/m²-K
      h_{ctg} = heat transfer coefficient, coating side   W/m²-K
      c_p = heat capacity of the web   J/kg-K
      h_w = thickness of the web   m
      T_a = air temperature   °C or K
      $T_{w,o}$ = initial web temperature   °C or K
      T_w = web temperature   °C or K

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$$\rho \quad = \text{web density} \qquad\qquad\qquad\qquad\qquad\qquad kg/m^3$$
$$\theta \quad = \text{time} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad s$$

It is better to use a thicker web, perhaps 180 μm (7 mil), rather than a thin web for this test, as it will have a higher heat capacity ($h_w \rho c_p$).

As reported by Cary and Gutoff[2] the heat transfer coefficient generally varies as the 0.39 power of the air plenum pressure or the 0.78 power of the air velocity. Thus, if the air nozzles are at the same configuration in all the drying zones then the heat transfer coefficient is equal to

$$h = h_o \left(\frac{P}{P_o}\right)^{0.39}$$

$$or \qquad\qquad\qquad\qquad (2)$$

$$h = h_o \left(\frac{V}{V_o}\right)^{0.78}$$

where h_o is the heat transfer coefficient at the reference pressure P_o or the reference velocity V_o. The reference pressure could be several hundred Pascal (about an inch of water pressure) and the reference velocity could be about 1000 m/min (3000 ft/min). The exponent 0.39 could vary by ±0.01 and the exponent 0.78 could vary by ±0.02 without significantly affecting the results. In the spreadsheet the reference air velocity is 4000 ft/min, but can be easily changed.

MODELLING THE CONSTANT RATE

A good model for constant rate drying of aqueous systems has been published recently[2]. The development starts by equating the heat transfer to the web on both sides to the mass transfer rate from the surface times the latent heat of evaporation. The Chilton-Colburn analogy[3] relates the mass transfer coefficient to the heat transfer coefficient. The end result is an implicit equation for the web temperature.

$$f(T_w) = T_w^2 + T_{a,ctg} \frac{T_w \left[P_w - P_a - K \left(T_{a,ctg} + \frac{h_{base}}{h_{ctg}} T_{a,base} \right) \right] + P_w T_{a,ctg}}{\left(1 + \frac{h_{base}}{h_{ctg}} \right) K T_{a,ctg} - P_a} = 0 \qquad (3)$$

where P_a = vapor pressure of the solvent in the drying air on the coating side   Pa
P_w = vapor pressure of the solvent at the web temperature   Pa
$T_{a,base}$ = temperature of the air on the base side   K
$T_{a,ctg}$ = temperature of the air on the coating side   K

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and the grouping K is

$$K = \left[c_{pa} + (c_{ps} - c_{pa})\left(\frac{P_a}{\pi - P_a}\right)\left(\frac{M_s}{M_a}\right)\right]N_{Le}^{2/3} \pi \left(\frac{M_a}{M_s}\right)\left(\frac{2}{\lambda}\right) \qquad (4)$$

where c_{pa} = heat capacity of the air   J/kg·K
      c_{ps} = heat capacity of solvent in the vapor phase   J/kg·K
      M_a = molecular weight of the air   daltons
      M_s = molecular weight of the solvent   daltons
      N_{Le} = Lewis number for the solvent in air, (α/D) -
      α = thermal diffusivity, $k/\rho c_p$ m₂/s
      D = diffusivity of solvent vapors in air   m²/s
      λ = heat of vaporization of the solvent   J/kg
      π = atmospheric pressure   Pa

These equations can be solved efficiently for the web temperature by the iterative Newton-Raphson procedure. Letting $i+1$ represent the $(i+1)$th iteration, then

$$T_{w,i+1} = T_{w,i} - \frac{f(T_{w,i})}{f'(T_{w,i})} \qquad (5)$$

where $f(T_{w,i})$ is the value of the expression in the ith iteration, and $f'(T_{w,i})$ is its derivative with respect to T_w. Thus

$$f'(T_w) = 2T_w + T_{a,ctg} \frac{P_w - P_a - K\left(T_{a,ctg} + \frac{h_{base}}{h_{ctg}}T_{a,base}\right) + T_w P_w' + T_{a,ctg}P_w'}{\left(1 + \frac{h_{base}}{h_{ctg}}\right)KT_{a,ctg} - P_a} \qquad (6)$$

Here P_w' is the derivative with respect to the temperature of the vapor pressure of the solvent, evaluated at the web temperature. The small variation in the group K with temperature is neglected.

When only single-sided drying is used, these equations will calculate the psychrometric chart for the particular solvent, and are similar to the equation derived by Keey[4] and to the equation presented by Pakowski and Mujumdar[5].

This model can be used for any solvent or solvent mixture. The vapor pressures of pure solvents are found from the Antoine equation

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$$\log P^o \; (in \; torr) \; = A - \frac{B}{C + t\,^oC} \qquad (7)$$

The average properties of a mixed solvent can be found from its composition in the liquid and in the vapor. For the vapor composition the activity coefficient of each component is needed. The vapor pressure of one component in a multicomponent mixture is

$$P_i = \gamma_i \, x_i \, P_i^o \qquad (8)$$

where P_i = vapor pressure of the ith component   Pa
x_i = mole fraction of the ith component in the liquid
γ_i = activity coefficient of the ith component

The activity coefficients can be found from one of several equations whose parameters depend on the pairwise interactions. Specifically, we use the Wilson equation, for which many of the pairwise parameters are given in the massive compilation of Gmehling et al.[6] and are also in the on-line Dortmund data base. The equations for the activity coefficients using the Wilson equations is given in Appendix A.

These equations assume that the coating is pure (mixed) solvent. But the coating also contains dissolved materials which will lower the vapor pressure. In aqueous coatings we have found that this vapor pressure reduction can be neglected with negligible error; in solvent coating, where many of the solids are dissolved rather than dispersed, the vapor pressure reduction is appreciable. The program includes a vapor pressure factor which can be adjusted between zero and one, and which is used to multiply the calculated vapor pressures in order to give the correct web temperature in the falling rate period. This may be regarded as a fudge factor, for it also will correct for other errors in the constant rate calculations.

The mole fraction in the vapor is found from

$$y_i = \frac{P_i}{\sum\limits_{i=1}^{n} P_i} \qquad (9)$$

All the physical properties, particularly the latent heat of evaporation, are functions of temperature. However, for some solvents this data is not available and, in view of the other approximations, we will assume that the physical properties are equal to their handbook values at about room temperature.

It has been observed that the web temperature in the constant rate period does not change much with distance down the dryer. This implies that one can calculate the initial

web temperature, and then assume that the liquid and vapor composition does not change further but remains constant at its initial value. This is obviously not so for a mixed solvent, for the less volatile species will become concentrated in the coating as drying progress. But this assumption greatly simplifies the model and still seems to give reasonably good predictions. One could assume that the solvent in the coating is at all times well-mixed and then calculate the change in concentration as in a simple distillation, but this obviously not be correct. One could also assume that evaporation takes place at the surface of the coating with no mixing at all of the solvent, but this is also not so, for the surface will be depleted with the more volatile component, which will then diffuse faster to the surface. The assumption of a single solvent that does not change composition greatly simplifies the model and allows mixed solvents to be handled in the same model as one-component solvents.

FALLING RATE MODELLING

Diffusion

In the falling rate period the solvent migrates by diffusion to the surface of the coating, where its concentration is in equilibrium with the drying air. If the air is solvent-free, then the surface concentration is equal to zero. The rate of evaporation is then the rate of diffusion to the surface. However, the diffusivity of the solvent in the coated layer is a function of the solvent concentration, as well as the temperature. We use a simple two-constant model for the concentration effect, based on free volume theory as earlier used by Beels and Claes[7]. Including the activation for the temperature effect, the resulting equation has three constants

$$D = A \exp\left[-\frac{B}{1 + \frac{2h_{solv}}{h_{solids}}}\right] \exp\left[-\frac{E}{RT}\right] \tag{10}$$

where A is the pre-exponential factor cm^2/s
B accounts for the concentration effect —
D is the diffusivity, cm^2/s
E is the activation energy for diffusion J/mol
R is the gas constant $8.314\ J/mol$
h_{solv} is the thickness contributed by the solvent in the coating μm
h_{solids} is the thickness contributed by the solids in the coating μm
T is the absolute temperature, K

The activation energy for diffusion can be assumed to be in the usual range (12,000 – 21000 J/mol, or 3000 – 5000 cal/mol), say 15,000 J/mol. The constants A and B would be found by trying different values in the finished model until the model fits the actual data. The final solvent level is decreased when the diffusivity is higher; thus higher values for A and lower values of B, which lead to higher diffusivities, predict lower solvent levels. It

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appears that the constants A and B affect little else, and that as long as A and B are chosen to give the correct final solvent level it does not matter what the individual values are. This means that one can choose one constant arbitrarily, and then vary the other constant until in a test run the correct final solvent level is predicted.

Surface Concentration

The surface concentration of solvent in the coating would be in equilibrium with the solvent in the air. If air is not recycled then the concentration of solvent in the air would normally be zero, and therefore the surface concentration of solvent in the coating would also be zero. This is what we have used in the model.

When air is recycled then the solvent level in the drying air can be found from a simple material balance. It is easy to add this to the spreadsheet.

If air is recycled then the surface concentration of solvent would no longer be zero and should be determined as a function of the solvent level in the air. The equilibrium levels may follow a relationship similar to that followed by moisture in gelatin, as found by Gehrmann and Kast[8]. Their results can be recast as

$$X = \frac{0.155 - 0.00075\, t}{\left(\ln \frac{1}{rh}\right)^{0.6}} \qquad rh > 0.2$$

$$X = (0.26 - 0.0015t)\,(rh)^{0.46} \qquad rh < 0.2 \tag{11}$$

where rh is the relative humidity
t is the temperature, °C
X is the ratio of solvent to solid (here water to dry gelatin)

One should be aware, however, that some solids are inert, and the ratio X should not include insoluble and non-swellable solids. The determination of the constants for this equation is not a simple matter.

The present model just assumes that the surface concentration of solvent is zero.

Finite Difference Equations

To find the solvent concentration of solvent in the coating the coating is divided into a number of slices, normally ten, and the diffusion equations are written in finite difference form. The finite difference analysis follows standard methods (see, for example, Mickley et al.[9]), except that the solvent diffusivities in, and the thicknesses of, each slice differ from each other and change with time. The solids in each slice remains constant and equal to the total solids coverage divided by the number of slices.

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Figure 1 illustrates some of the notation for the slices. Position 0 is at the base, position 1 at the top of the first slice, position s at the surface. Position m is at the top of the mth slice. h_m is the thickness of the mth slice, and the diffusivity of solvent in that slice is D_m. Let us make a material balance on the slice centered at position m; that is, from half-way between positions m-1 and m, to halfway between position m and m+1. The rate of accumulation is equal to the rate of diffusion into the slice minus the rate of diffusion out of the slice, or, considering the time interval from time n to time n+1,

$$\left(\frac{C_{m,n+1} - C_{m,n}}{\Delta \theta} \right)\left(\frac{h_{m+1}}{2} + \frac{h_m}{2} \right) = D_m\left(\frac{C_{m-1,n} - C_{m,n}}{h_m} \right) - D_{m+1}\left(\frac{C_m - C_{m+1}}{h_{m+1}} \right) \quad (12)$$

where $C_{m,n}$ is the concentration of solvent in the mth slice at time n g/cm^3

     $\Delta \theta$ is the time interval between n and n+1 s

Solving for the concentration at the next time interval yields

$$C_{m,n+1} = C_{m,n} + \frac{2 \Delta \theta}{h_m + h_{m+1}}\left[\frac{C_{m-1,n} D_m}{h_m} - C_{m,n}\left(\frac{D_m}{h_m} + \frac{D_{m+1}}{h_{m+1}} \right) + \frac{C_{m+1,n} D_{m+1}}{h_{m+1}} \right] \quad (13)$$

where D_m is evaluated at the mean concentration in the slice, $(C_{m-1}+C_m)/2$. This equation is good for all the intermediate slices. For the bottom slice, the material balance is

$$\left(\frac{C_{0,n+1} - C_{0,n}}{\Delta \theta} \right)\frac{h_1}{2} = 0 - D_1\left(\frac{C_{0,n} - C_{1,n}}{h_1} \right) \quad (14)$$

Therefore

$$C_{0,n+1} = C_{0,n} - \frac{2 D_1 \Delta \theta}{h_1^2} (C_{0,n} - C_{1,n}) \quad (15)$$

The flow to the surface by diffusion, and therefore the evaporation rate, is just

$$\textit{Evaporation rate} = D_s\left(\frac{C_{s-1} - C_s}{h_s} \right) \quad (16)$$

where C_s is the surface concentration, and is in equilibrium with the solvent level in the air. With dry air, it is zero.

The thickness of a slice changes with time because solvent leaves the slice by diffusion to the surface. If at time zero we form a number of identical slices, each with s g/m^2 of solids at an average density of ρ_{solids} g/cm^3, and we have W_{solvm} g/m^2 of solvent in

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the slice, and if there is no change in volume on dissolution of the solids, then the thickness of the slice is

$$h_m = \left(\frac{g \, \frac{g}{m^2}}{\rho_{solids} \frac{g}{cm^3}} + \frac{W_{s,m} \, \frac{g}{m^2}}{\rho_{solv} \frac{g}{cm^3}} \right) \frac{cm^3}{m^2} \; (= \mu m) \qquad (17)$$

But the coverage, $W_{solv,m}$, is related to the concentration by

$$C_m = \frac{W_{solv,m} \, \frac{g}{m^2}}{h_m \, \frac{cm^3}{m^2}} \qquad (18)$$

Replacing $W_{solv,m}$ in equation 17 by its value from equation 18 gives

$$h_m = \frac{g}{\rho_{solids}} + \frac{h_m C_m}{\rho_{solv}} \qquad (19)$$

or

$$h_m = \frac{\frac{g}{\rho_{solids}}}{\left(1 - \frac{C_m}{\rho_{solv}} \right)} \qquad (20)$$

There are certain stability requirements for $\Delta \theta$ and h_m. In equations 5 and 7 the concentration at the present time must not have a negative effect on the concentration at the future time. This is equivalent to saying that, omitting subscripts,

$$\frac{2D\Delta\theta}{h^2} \leq 1 \qquad (21)$$

or

$$\frac{h^2}{D\Delta\theta} \geq 2 \qquad (22)$$

This grouping in equation 22 is called the modulus, and we see that it must be at least two for the computation to be stable. Since the diffusivity is a strong function of concentration, we might expect that the modulus would be lowest at the base where the concentration of solvent and the diffusivity are highest. On the other hand, because the concentration of solvent is highest there the slice thickness would be greatest, which would

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tend to give a high modulus. It turns out that we have to check the modulus for all the slices, and set the lowest modulus equal to two in determining the maximum time interval. We may use shorter time intervals. For example, we always want at least ten time intervals in each dryer zone. The maximum time interval for stability is recalculated after each time period.

The time interval is directly proportional to the square of the thickness of the slices. If the time interval is too short, an excessive amount of computing time may be consumed. We start with ten slices, but if the time intervals are too short then the number of slices could be decreased. This would involve some changes in the spreadsheet.

Web Temperature in the Falling Rate Period

The web temperature in the falling rate period is found by a heat balance with the rate of accumulation of heat in the web plus coating being equal to the input of heat by heat transfer from the air (on one or on both sides) minus the heat output by the latent heat of the evaporating solvent. Thus, in consistent units

$$(\Sigma W_i c_{p,i}) \frac{\Delta T_{web}}{\Delta \theta} = h_{ctg} (T_{a,ctg} - T_w) + h_{base} (T_{a,base} - T_w) - \lambda \frac{\Delta W_{solv}}{\Delta \theta} \quad (23)$$

where W_i is the coverage of the ith component and the rate of evaporation, $\Delta W_{solv}/\Delta \theta$, is taken as positive. This equation allows us to solve for the web temperature after every time interval

END OF THE CONSTANT RATE PERIOD

At the start, the evaporation rate is calculated for the constant rate period and also assuming falling rate conditions; that is, assuming a uniform solvent concentration everywhere except at the surface. The time at which the calculated falling rate evaporation rate becomes less than the constant rate evaporation rate marks the end of the constant rate period and the start of the falling rate.

THE SPREADSHEET

The spreadsheet consists of four worksheets. Sheet A contains the input data and lists some of the important output data. Most of sheet A is printed out, as in Figure 2, along with linear and semi-logarithmic graphs of the temperatures and solvent levels in the dryer, Figures 3 and 4. Sheet B is where most of the calculations are carried out. Sheet C

contains the data base for the solvents, and the calculations of the average solvent properties are calculated here. The macros used to run the program are on sheet *D*.

All calculations are carried out in SI units. However, the input data are entered on sheet *A*, Figure 2, in whatever units one wishes to use. The data entered include the wet load, the percent solids, the base thickness, the coating speed, and the air velocities and temperature. The units are converted to SI units when copied to sheet B, Figure 5. If the solvent is a mixture the percentages of each component are also entered on sheet *A*. The constants for the diffusivity equation can be changed in sheet *A*. Sheets *A* and *B* can be changed so that air plenum pressures are used in place of air velocities. The important output data, namely the temperatures and solvent levels at the end of each zone, are gathered on sheet *A*.

The calculations are done on sheet *B*. The far right side, not shown in Figure 5, contains a table of all the named variables and their ranges. The average physical properties of the solvent are calculated on Sheet *C* and then copied to the upper left of this sheet, see Figure 5, under *Constant Rate Properties* and *Falling Rate Properties*. To the right of this is the *Input Data* which is copied from sheet *A*, and also some *Calculated Data*. Further to the right is a section, shown in Figure 6, where the vapor-liquid equilibrium is calculated using the Wilson equation. Antoine constants for the Antoine vapor pressure equation and the pair-wise Wilson constants are given here, as copied from Sheet *C*. For a single-component solvent the Wilson constants are not needed. The mole fraction in the liquid, x, is found in Sheet *C* and is copied to the right of the Wilson constants. The calculations for the mole fraction in the vapor in each zone is carried out just below. The Wilson expression Λ_{ij} (see Appendix *A*) is given as L_{ij} in the spreadsheet. We assume that the composition of a mixed solvent in the coating does not change in the course of drying, and therefore the vapor composition, used only to find the vapor pressure, P, and the derivative of the vapor pressure with temperature, P', also does not change in the course of drying except for changes in temperature. The justification for this assumption will be discussed later. The vapor pressure and its derivative are used to find the web temperature in the constant rate regions.

The constant rate calculations for web temperature are carried out in the table beneath *Falling Rate Properties*, as shown in Figure 5. The Newton-Raphson iterative procedure is used to solve the implicit equation for the web temperature. The method converges rapidly, and twelve iterations are normally used. The iterations have converged when the numbers in the column headed $f(T_w)$, defined by equation 4, are small, less than about 10^{-3}. They are usually much less. The heat transfer coefficients are calculated from the air velocities, and the evaporation rate is just the heat transfer rate divided by the latent heat of vaporization.

Underneath this constant rate table is the section headed *Location of the End of Constant Rate*, Figure 7. Here the rate of diffusion to the surface is compared to the constant rate evaporation rate. When the diffusion rate is less it means that the constant

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rate period is over and the calculations would move to a lower section to calculate the falling rate drying. The suggested time interval for the constant rate calculations is given in the second line below the heading. It must be smaller than the time it takes to traverse one-tenth of a zone, because we want ten data points per zone in the summary table. The solvent level for each time interval in the constant rate period is calculated in this section. When at least one-tenth of a zone is traversed, the data are recorded in a *Data Summary* table. When the distance traversed brings the coating into a new zone, the data for the new zone are brought into this constant rate section, and also the web temperature and the solvent level are recorded in sheet A.

The falling rate calculations are carried out in the table marked Falling Rate Calculations, Figure 8, in the section below the *Location of End of Constant Rate.* Here the diffusion calculations are carried out for each slice. The maximum time interval for the falling rate calculations, recorded on the left side below this table, is the lesser of the constant rate time interval or the maximum interval for stable iterations, taken as the smallest time in the right hand column of the table and recorded below the table in the right column.

When the calculations are concluded the *Data Summary* table, Figure 9, located to the right of the calculations, is completed. The distances in the dryer can be converted from meters, and the temperatures from Celsius, if desired. Then linear and semi-logarithmic graphs of the temperatures and solvent levels versus distance in the dryer, Figures 3 and 4, as well as a copy of most of sheet A, Figure 2, are printed out.

There is one column set apart on Figure 9, on the left side, and headed *To Copy to T-web, C.* On the actual spread sheet it is to the right of the constant rate calculations. If ever the iterative procedure does not converge, and the constant rate table gets filled with error messages, *ERR*, then one has to reset the procedure. One does this by replacing the starting point for the web temperatures in the column headed *T-web, C*, with reasonable temperatures, such as 25°C (note that a number 25 is just under this little column). Then one hits the calculation key, F9, once. This one calculation removes all the error messages. Then one should copy the formulas in the column headed *To Copy To T-web, C* to the *T-web, C* column, and start again. This procedure is used by the macros when changing solvents, and one can do this procedure in an easier manner by starting the macro \Q to re-specify the solvent components, by hitting alternate-*Q.*

Sheet *D* contains all the macros and subroutines, with explanations of what they do.

RUNNING THE SPREADSHEET

After entering the data start the calculations by running macro \A by hitting Alternate-*A.* The program takes about five minutes to run. The running time depends on the final solvent levels. The lower the solvent levels the longer it takes to run the program.

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To change solvents hit Alternate-Q. The macro \Q shows a screen with a list of solvents and solvent pairs, as in Table I, and asks for the first solvent number. It then asks for the second and third solvent numbers. If the second solvent number is zero then a single-component solvent is used and its concentration is entered as 100% on sheet A. If the third solvent number is zero then a two-component solvent is used and the composition entered on sheet A is 50% for each. The correct solvent concentration then has to be inserted. For a three-component solvent the solvent concentrations are left as they had been. When two- or three-component solvents are used the correct concentrations have to be entered.

If a mixed solvent is used, the components have to be chosen among those pairs for which the Wilson constants in the table. A three-component solvent would require three solvent pairs, A-B, A-C, and B-C. Sheet C contains data for 14 solvents and 44 solvent pairs, out of a possible 91 solvent pairs (see Table I). It is fairly easy to enter new solvents and additional data in Sheet C.

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NOMENCLATURE

A	constant in Antoine equation	-
A	pre-exponential factor in diffusivity equation	m2/s
A_{12}, A_{21}	constants in Wilson equation	cal/mol
B	constant in Antoine equation	°C
B	constant in diffusivity equation	-
c_p	heat capacity	J/kg·K
C	constant in Antoine equation	°C
C	concentration of solvent	g/cm³
D	diffusivity	m²/s
E	activation energy for diffusion	J/mol
h	thickness	m
h	heat transfer coefficient	W/m²·K
k	thermal conductivity	W/m²·(K/m)
K	grouping of constants defined by equation 4	Pa/k
M	molecular weight	daltons
N_{Le}	Lewis number, α/D	-
P	pressure or vapor pressure	Pa
P_a	vapor pressure of solvent in the drying air	Pa
P_w	vapor pressure of solvent at the web temperature	Pa
R	gas constant	J/mol·K or cal/mol·K
rh	relative humidity	-
s	solids in a slice of the coating	g/m²
t	temperature	°C
T	temperature	K
V	air velocity	m/s
W	coverage or amount of material	g/m²
x	mole fraction in the liquid	-
X	ratio of solvent to dissolved solids	-
y	mole fraction in the vapor	-

Greek

α	thermal diffusivity, $k/\rho c_p$	m²/s
θ	time	s
λ	heat of vaporization	J/kg
π	atmospheric pressure	Pa

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Superscripts

o	pure single-component solvent
'	differentiation with respect to temperature

Subscripts

a	air
$base$	base
ctg	coating
i	component i
m	slice m
n	time n
o	initial or reference condition
s	surface
$solv$	solvent
$solids$	solids
w	web

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Appendix A

Calculation of Activity Coefficients Using the Wilson Equation

From Gmehling et al. (1977)

The Wilson equation for the activity coefficient of component i in a multicomponent mixture is

$$\ln \gamma_i = -\ln\left(\sum_{j=1}^{m} x_j \Lambda_{ij}\right) + 1 - \sum_{k=1}^{m} \frac{x_k \Lambda_{ki}}{\sum_{j=1}^{m} x_j \Lambda_{kj}}$$

where

$$\Lambda_{ij} = \frac{V_j^L}{V_i^L} \exp\left(-\frac{(\lambda_{ij} - \lambda_{ii})}{RT}\right)$$

$$\Lambda_{ii} = \Lambda_{jj} = 1$$

$$\lambda_{ij} = \lambda_{ji}$$

V_i^L	is the molar volume of pure i	cm^3/mol
R	is the gas constant	1.987 cal/mol·K
A_{12}	$= \lambda_{12} - \lambda_{11}$, a pairwise Wilson constant	cal/mol
A_{21}	$= \lambda_{12} - \lambda_{22}$, the second pairwise Wilson constant	cal/mol

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Table I

AVAILABLE SOLVENTS AND SOLVENT PAIRS

Wilson Constants are entered for the listed solvent pairs.

No	Solvent	Solvent numbers for solvents paired with listed solvent											
1	Acetone	-	2		4	5	6	7				11		13	14
2	n-Butanol	1	-			5	6					11	12	13	14
3	Cyclohexanone		•											13	14
4	Ethanol	1			-	5	6	7	8					13	14
5	Ethyl acetate	1	2		4	-	6	7				11		13	14
6	Methanol	1	2		4	5	-	7	8		10	11	12	13	14
7	Methyl ethyl ketone	1			4	5	6	-				11		13	14
8	Methyl i-propyl ketone				4		6		-			11			
9	Methyl n-propyl ketone									-		11		13	
10	Methylene chloride						6				•				
11	i-Propanol	1	2			5	6	7	8	9		-	12	13	14
12	Tetrahydrofuran		2				6					11	-		14
13	Toluene	1	2	3	4	5	6	7		9		11		-	
14	Water	1	2	3	4	5	6	7				11	12		-

List of Figures

Figure 1. Finite difference notation for the slices in the coating for the falling rate period.

Figure 2. Output table showing a portion of worksheet A with the input and calculated data.

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Figure 4. Semi-logarithmic output graph, otherwise similar to Figure 3.

Figure 5. Portion of sheet B showing the data from sheet A converted to SI units, and the results of the constant rate calculations.

Figure 6. Portion of sheet B showing the vapor pressure calculations for mixed solvents.

Figure 7. The calculations for the end of the constant rate period, and the solvent level in the constant rate period.

Figure 8. The falling rate calculations.

Figure 9. The top portion of the Data Summary. The data for Figures 3 and 4 are taken from this table.

D_s, h_s

s

s-1

m+1

D_{m+1}, h_{m+1}

m

D_m, h_m

m-1

D_{m-1}, h_{m-1}

1

D_1, h_1

0
Base
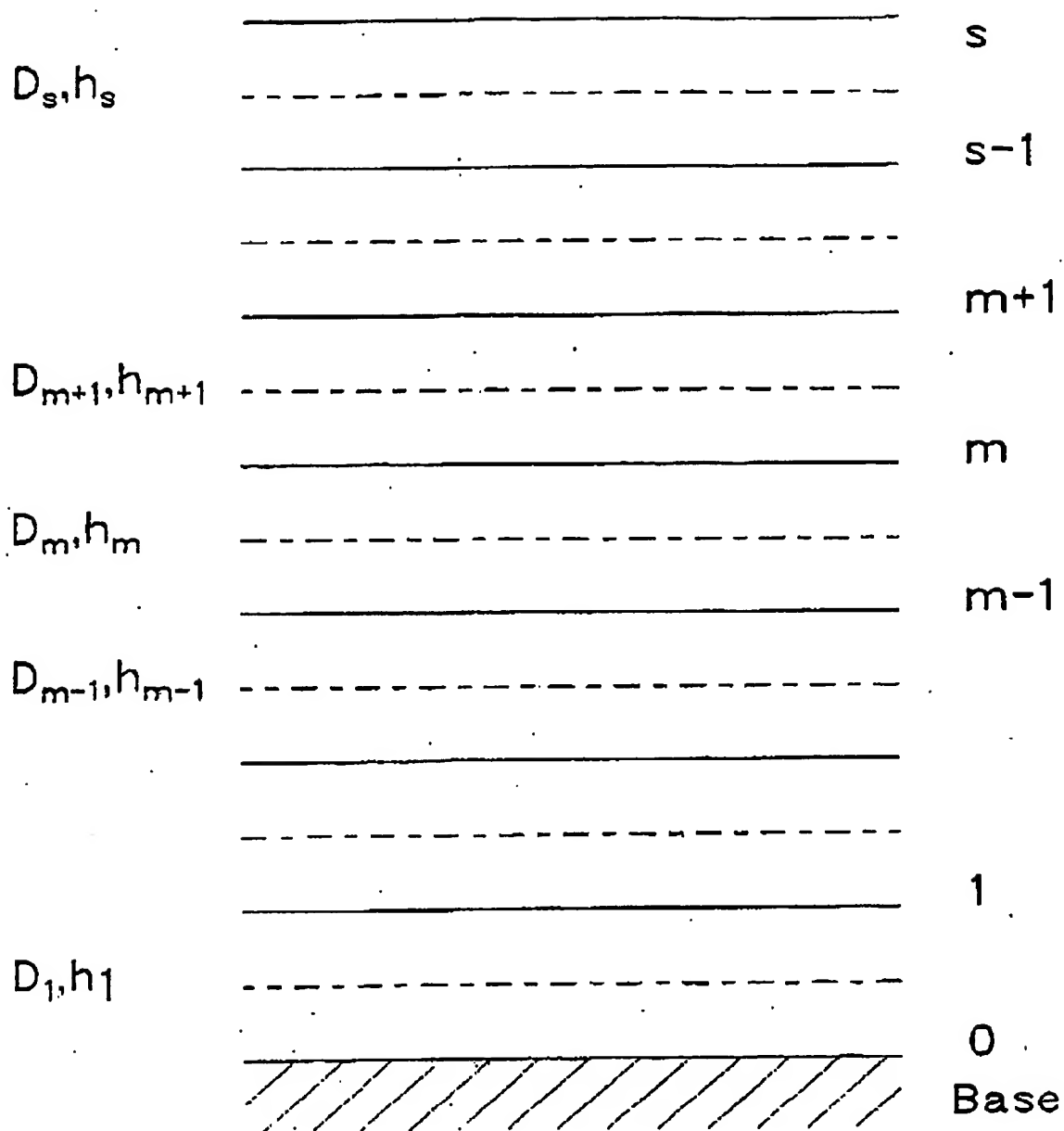
Figure 1. Finite difference notation for the slices in the coating for the falling rate period.

```
DRYING: CONSTANT AND FALLING RATE        Test Example 1
Programmed by E. B. Gutoff                v. 3.01 - February 1993
               See NOTES below
INPUT DATA
Wet load, g/m^2           100.00  SOLVENT    wt %  DIFFUSIVITY CONSTANTS
% solids                   25.00  Acetone   35.00  A, cm^2/s   11000
Base id                    Mylar  MeOH      35.00  B            1.6
Base thickness, mils        5.00  HEX       30.00  E, J/mol    15000
Coating speed, ft/min     100.00  Total    100.00
```

Zone	Length ft	Cum Length ft	AIR VELOCITY ft/min ctd side	back side	T-Dry Ctg F	T-dry Base F	T-web at end F	Solvent at end g/m^2
1	20.0	20.0	3000	3000	80.0	80.0	75.9	34.200
2	20.0	40.0	3000	3000	90.0	90.0	87.2	16.987
3	20.0	60.0	3000	3000	100.0	100.0	97.8	8.066
4	20.0	80.0	3000	3000	120.0	120.0	118.5	3.591
5	20.0	100.0	3000	3000	120.0	120.0	119.3	1.681
6	20.0	120.0	3000	3000	120.0	120.0	119.6	0.823
7	20.0	140.0	3000	3000	120.0	120.0	119.8	0.413

The constant rate period is over   3   feet into the dryer.

Figure 2. Output table showing a portion of worksheet *A* with the input and calculated data.

Dryer Summary
Test Example 1

Figure 3. Linear output graph, showing web temperatures and coating solvent levels throughout the length of the dryer.

Dryer Summary
Test Example 1

Figure 4. Semi-logarithmic output graph, otherwise similar to Figure 3.

DRYING: CONSTANT AND FALLING RATE   Test Example 1
Programmed by E. B. Gutoff   v. 3.01 February 1993

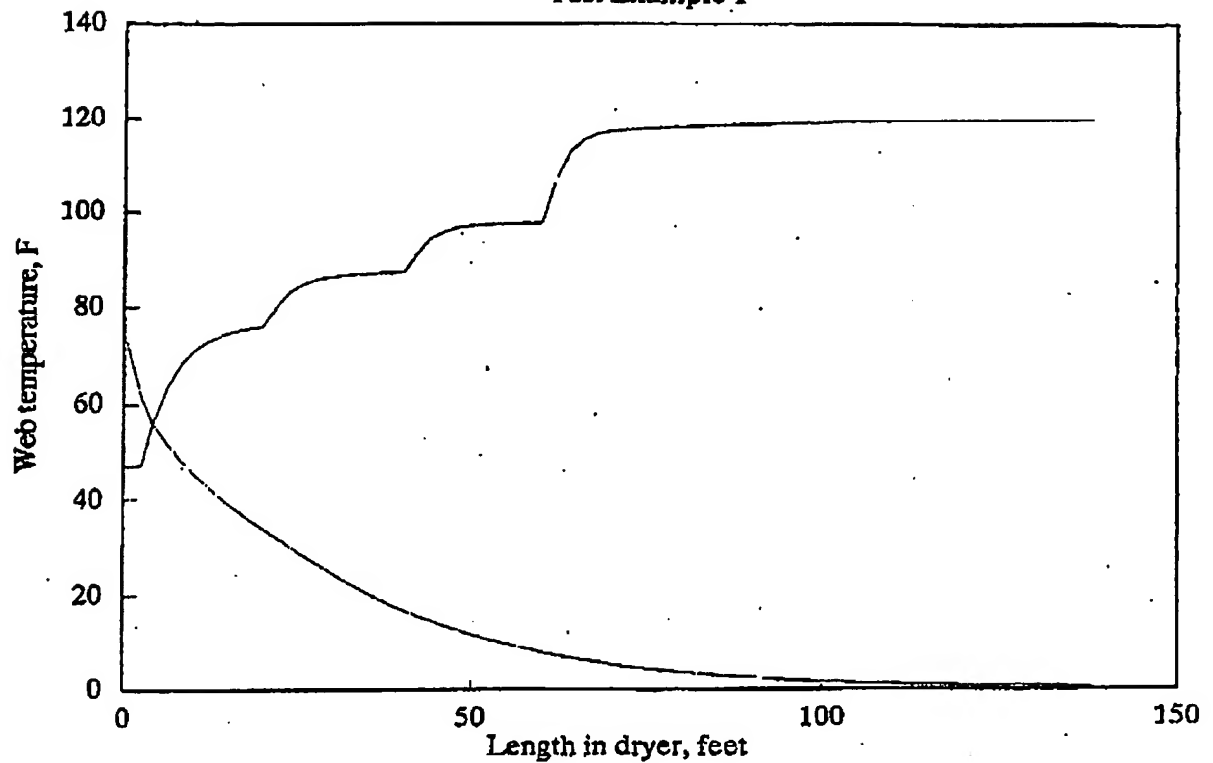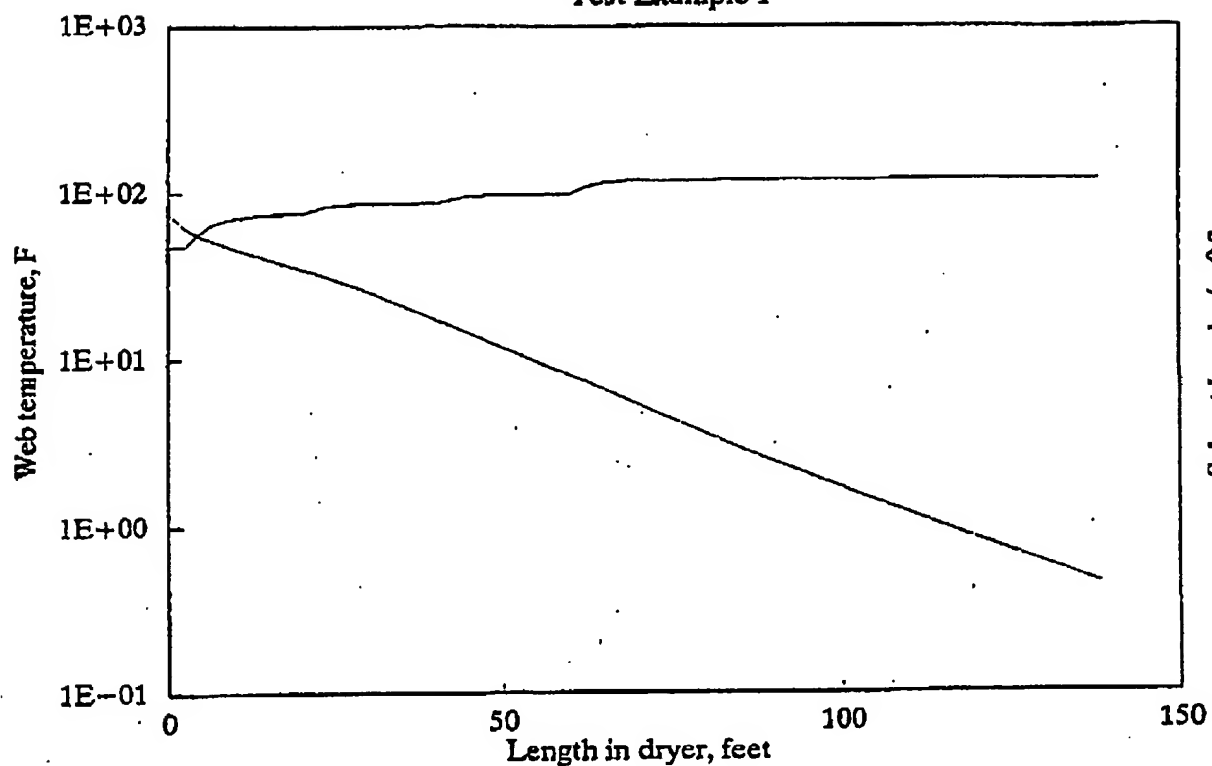|			
h @ 4000fpm,W/ntm-K	100.00	INPUT DATA	
		Wet load, g/m^2	100.00
		% solids	25.00
CONSTANT RATE PROPERTIES		Base id	Mylar
MM solvent	58.32	Base thickness, µm	127.00
Cp vapor, J/Kg-K	1311.64	Coating speed, m/min	30.48
Cp air, J/Kg-K	1005.00		
Ht. vapor, J/g	660.81		
Lewis no.	2.27	CALCULATED DATA	
Vap press reduction	0.50	Solvent ctd, g/m^2	75.00
		Solids ctd, g/m^2	25.00
SOLIDS COATED		Solids thickness, µm	21.55
Density, g/cm^3	1.16	Solvent thickness,µm	94.28
Specific heat	0.28	Base wt, g/m^2	128.27
		Total dryer length	30.48
BASE		Total time in dryer, s	60.0
Density, g/cm^3	1.01	Solids thick/slice, µm	2.16
Specific heat	0.40		

FALLING RATE PROPERTIES
    Diffusion constants
        A   11000 E-8 cm^2/s
        B   1.60
        E   15000 J/mol
    Ht vapor, J/g   711.4
    Specific ht liq   0.558
    Dens solv, g/cm^   0.796
    Number slices   10.00

Constant Rate Calculations

Zone	Length m	COATED SIDE Air Vel ft/min	h W/m^2-K	BACK SIDE Air Vel ft/min	h W/m^2-K	T-Dry Ctg C	T-dry Base C	EvapRate g/m^2-s	Cum Length m
1	6.10	3000	79.9	3000	79.9	26.7	26.7	4.43	6.10
2	6.10	3000	79.9	3000	79.9	32.2	32.2	5.05	13.19
3	6.10	3000	79.9	3000	79.9	37.8	37.8	5.78	18.29
4	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	24.38
5	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	30.48
6	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	36.58
7	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	42.67

Zone	T-web C	T-web K	K/1000	p-dev kPa	p-web kPa	p'-web kPa/K	f(T-w)	f'(T-w)	T-web new K
1	8.3	281.5	0.30688	0	5.445	0.291	7E-15	5E+02	281.5
2	11.4	284.5	0.30688	0	6.176	0.324	0E+00	6E+02	284.5
3	13.9	287.0	0.30688	0	7.036	0.361	-7E-15	6E+02	287.0
4	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7
5	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7
6	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7
7	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7

Figure 5. Portion of sheet *B* showing the data from sheet *A* converted to SI units, and the results of the constant rate calculations.

Programmed by E. B. Gutoff V. 3.01 February 1993

h @ 4000fpm,W/m*m-K	100.00	INPUT DATA			
		Wet load, g/m^2	100.00		
		% solids	25.00		
CONSTANT RATE PROPERTIES		Base id	Mylar		
MW solvent	50.32	Base thickness, µm	127.00		
Cp vapor, J/kg-K	1311.64	Coating speed, m/min	30.48		
Cp air, J/kg-K	1005.00				
Ht. vapor, J/g	660.81				
Lewis no.	2.27	CALCULATED DATA			
Vap press reduction	0.50	Solvent ctd, g/m^2	75.00		
		Solids ctd, g/m^2	25.00		
SOLIDS COATED		Solids thickness, µm	21.55		
Density, g/cm^3	1.16	Solvent thickness, µm	94.28		
Specific heat	0.28	Base wt, g/m^2	128.27		
		Total dryer length	30.48		
BASE		Total time in dryer, s	60.0		
Density, g/cm^3	1.01	Solids thick/slice, µm	2.16		
Specific heat	0.40				
FALLING RATE PROPERTIES					
Diffusion constants					
λ	11000 E-8 cm^2/s				
B	1.60				
E	15000 J/mol				
Ht vapor, J/g	711.4				
Specific ht liq	0.558				
Dens solv, g/cm^	0.796				
Number slices	10.00				

Constant Rate Calculations

Zone	Length m	COATED SIDE Air Vel ft/min	h W/m^2-K	BACK SIDE Air Vel ft/min	h W/m^2-K	T-Dry Ctg C	T-dry Base C	EvapRate g/m^2-s	Cum Length m
1	6.10	3000	79.9	3000	79.9	26.7	26.7	4.43	6.10
2	6.10	3000	79.9	3000	79.9	32.2	32.2	5.05	12.19
3	6.10	3000	79.9	3000	79.9	37.8	37.8	5.78	18.29
4	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	24.38
5	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	30.48
6	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	36.58
7	6.10	3000	79.9	3000	79.9	48.9	48.9	7.35	42.67

Zone	T-web C	T-web K	K/1000	p-dev kPa	p-web kPa	p'-web kPa/K	f(T-w)	f'(T-w)	T-web new K
1	8.3	281.5	0.30688	0	5.445	0.291	7E-15	5E+02	281.5
2	11.4	284.5	0.30688	0	6.176	0.324	0E+00	6E+02	284.5
3	13.9	287.0	0.30688	0	7.036	0.361	-7E-15	6E+02	287.0
4	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7
5	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7
6	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7
7	18.5	291.7	0.30688	0	8.862	0.440	0E+00	7E+02	291.7

Figure 5. Portion of sheet *B* showing the data from sheet *A* converted to SI units, and the results of the constant rate calculations.

Solvent	wt %	V-iL cc/mol	Antoine Constants			Wilson Constants			x
			A	B	C	A-i1	A-i2	A-i3	
Acetone	35.00	74.05	7.11714	1210.595	229.664	—	-170.1753	-232.9286	0.2855
MeOH	35.00	40.73	8.08000	1582.300	239.730	594.1757	—	767.5030	0.5175
MEK	30.00	90.17	7.06356	1261.340	224.969	476.87	-217.5920	—	0.1971
	100.00								1.0000

Zone	Solv	vp, Pa	L-i1	L-i2	L-i3	gamma	P, Pa	y	p'
1	1	14325	1.0000	0.7456	1.8466	1.2817	2621	0.481	
	2	6713	0.6285	1.0000	0.5614	1.1768	2044	0.375	
	3	6062	0.3501	0.6665	1.0000	1.3065	780	0.143	
Sum--->							5445	1.000	291
2	1	16584	1.0000	0.7432	1.8385	1.1944	2827	0.458	
	2	8007	0.6356	1.0000	0.5696	1.1798	2436	0.394	
	3	7105	0.3533	0.6637	1.0000	1.3036	913	0.148	
Sum--->							6176	1.000	324
3	1	18707	1.0000	0.7412	1.8318	1.1926	3184	0.453	
	2	9258	0.6415	1.0000	0.5765	1.1749	2814	0.400	
	3	8095	0.3559	0.6615	1.0000	1.3011	1038	0.148	
Sum--->							7036	1.000	361
4	1	23139	1.0000	0.7377	1.8200	1.1894	3928	0.443	
	2	11964	0.6522	1.0000	0.5889	1.1734	3632	0.410	
	3	10191	0.3607	0.6575	1.0000	1.2968	1302	0.147	
Sum--->							8862	1.000	440
5	1	23139	1.0000	0.7377	1.8200	1.1894	3928	0.443	
	2	11964	0.6522	1.0000	0.5889	1.1734	3632	0.410	
	3	10191	0.3607	0.6575	1.0000	1.2968	1302	0.147	
Sum--->							8862	1.000	440

Figure 6, Portion of sheet B showing the vapor pressure calculations for mixed solvents.

LOCATION OF END OF CONSTANT RATE

First

Web.temperature, C		8.3	8.3	8.3	47.02 temp, F	
Delta t, s, suggest 0.50	Use	0.50 Max delta time=			1.20 s, for 0.1 zone	
Iteration		0	1	2	3	
Time, s		0.00	0.50	1.00	1.50	
Location into dryer, m		0.00	0.25	0.91	0.76	9.65 2.54
Solvent concn at surface		0.00	0.00	0.00	0.00	
Thickness of half surf layer, μm		1.08	1.08	1.08	1.08	
Solvent in half surf layer, g/m^2		0.00	0.00	0.00	0.00	
Total other solvent, g/m^2		75.00	72.78	71.37	69.15	
Total solvent, g/m^2		75.00	72.78	71.37	69.15	
Solvent in each layer, g/m^2		7.89	7.66	7.51	7.28	
Thickness of other layers, μm		12.08	11.79	11.60	11.31	
Solvent concn in layers, g/cm^3		0.65	0.65	0.65	0.64	
Diffusivity, μ^2/s		13.61	13.52	13.45	13.35	
Evaporation rate, g/m^2-s		4.13	4.08	4.04	3.99	4.43 is CR rate

Zone	Previous	0	This zone	1	2 is next zone
Zone length, m		6.10		6.10	
Increment of length, m				0.25	
Iterations in constant rate period		1			
Length to end of zone				6.10	0.00 to end prev zone
End of Constant Rate, m into dryer		0.76 in zone	1	1	

Figure 7. The calculations for the end of the constant rate period, and the solvent level in the constant rate period.

FALLING RATE CALCULATIONS

Slice n	Conc $C-n$ g/cm^3	Thick h-n µm	Solvent W-n g/m^2	Diff D-n µm^2/s	New-C $C-n,n+1$ g/cm^3	Max del Time s
1	0.03	2.24	0.07	9.18	0.03	0.27
2	0.03	2.24	0.07	9.17	0.03	0.27
3	0.03	2.23	0.06	9.14	0.03	0.27
4	0.03	2.23	0.06	9.08	0.03	0.27
5	0.02	2.22	0.05	9.00	0.02	0.27
6	0.02	2.21	0.04	8.89	0.02	0.27
7	0.02	2.20	0.03	8.75	0.01	0.28
8	0.01	2.18	0.02	8.60	0.01	0.28
9	0.01	2.17	0.01	8.44	0.01	0.28
10	0.00	2.16	0.00	8.27	0.00	0.28

SUM   22.07   0.41

No. of slices	10.00		
Solids per slice, g/m^2	2.50		
Iterations	296		
Delta time, s	0.27	Max possible delta time	0.27
Time, s	84.26	Next time	84.53
Location into dryer, m	42.60	Zone length, m	6.10
Evaporation rate, g/m^2-s	0.02		
Zone: Prev= 6 ; This=	7	Next zone	8
Web temperature, C	48.79	Next temp	48.79
Length to end of zone, m	42.67	To end of previous zone	36.58
T-air, ctg side, C	48.9	Web temp, F	119.82
T-air, base side, C	48.9		
h ctg side, W/m^2-K	79.9		
h base side, W/m^2-K	79.9		

Figure 8. The falling rate calculations.

| | | DATA SUMMARY | | | | Iteration | | | |
Count N	Approx Zone	Length m	Time s	EvapRat g/m^2-s	T-web C	Solvent g/m^2	Delta t s	Length ft	T-web P
71	0.0	0.00	0.00	4.43	8.3	75.000		0.0	47.0
72	0.1	0.76	1.50	1.22	8.45	61.47	0.31	2.5	47.2
	0.2	1.25	2.46	0.98	13.05	56.35	0.33	4.1	55.5
	0.3	1.92	3.77	0.77	17.50	51.76	0.33	6.3	63.5
	0.4	2.58	5.09	0.67	20.27	48.07	0.33	8.5	68.5
	0.5	3.08	6.07	0.62	21.60	45.64	0.33	10.1	70.9
	0.6	3.75	7.39	0.56	22.77	42.72	0.33	12.3	73.0
————	0.7	4.43	8.71	0.52	23.50	40.06	0.33	14.5	74.3
To Copy	0.8	4.94	9.72	0.49	23.87	38.20	0.34	16.2	75.0
To	0.9	5.62	11.06	0.46	24.22	35.87	0.34	18.4	75.6
T-web, C	1.0	6.14	12.08	0.44	24.41	34.20	0.34	20.1	75.9
————	1.1	6.83	13.44	0.43	26.97	32.06	0.33	22.4	80.5
-273.2	1.2	7.33	14.43	0.42	28.37	30.51	0.32	24.1	83.1
-273.2	1.3	7.98	15.72	0.41	29.39	28.48	0.33	26.2	84.9
-273.2	1.4	8.63	16.99	0.40	29.91	26.52	0.32	28.3	85.8
-273.2	1.5	9.27	18.25	0.38	30.20	24.63	0.32	30.4	86.4
-273.2	1.6	9.91	19.51	0.37	30.38	22.82	0.32	32.5	86.7
-273.2	1.7	10.39	20.46	0.36	30.47	21.52	0.32	34.1	86.8
-273.2	1.8	11.03	21.72	0.35	30.56	19.89	0.32	36.2	87.0
————	1.9	11.68	22.98	0.34	30.63	18.38	0.32	38.3	87.1
25	2.0	12.32	24.25	0.33	30.68	16.99	0.32	40.4	87.2
	2.1	12.80	25.21	0.33	32.54	16.02	0.31	42.0	90.6
	2.2	13.43	26.43	0.33	34.55	14.82	0.30	44.0	94.2
	2.3	14.03	27.61	0.33	35.47	13.73	0.29	46.0	95.9
	2.4	14.77	29.07	0.32	35.99	12.49	0.29	48.5	96.8
	2.5	15.36	30.24	0.31	36.19	11.59	0.29	50.4	97.1
	2.6	15.95	31.40	0.30	36.31	10.77	0.29	52.3	97.4
	2.7	16.54	32.57	0.29	36.39	10.01	0.29	54.3	97.5
	2.8	17.14	33.74	0.28	36.46	9.31	0.29	56.2	97.6
	2.9	17.73	34.91	0.27	36.51	8.66	0.29	58.2	97.7
	3.0	18.33	36.09	0.26	36.57	8.07	0.30	60.1	97.8
	3.1	18.93	37.26	0.26	41.55	7.51	0.28	62.1	106.8
	3.2	19.61	38.60	0.27	45.19	6.88	0.26	64.3	113.3
	3.3	20.13	39.62	0.26	46.44	6.41	0.25	66.0	115.6
	3.4	20.76	40.87	0.25	47.19	5.88	0.25	68.1	116.9
	3.5	21.39	42.11	0.23	47.54	5.39	0.25	70.2	117.6
	3.6	22.02	43.35	0.22	47.73	4.95	0.25	72.3	117.9
	3.7	22.65	44.59	0.20	47.85	4.55	0.25	74.3	118.1
	3.8	23.29	45.84	0.19	47.94	4.18	0.25	76.4	118.3
	3.9	23.79	46.84	0.18	48.00	3.91	0.25	78.1	118.4
	4.0	24.43	48.09	0.17	48.07	3.59	0.25	80.2	118.5
	4.1	25.07	49.35	0.16	48.13	3.31	0.25	82.3	118.6
	4.2	25.71	50.61	0.14	48.18	3.05	0.25	84.4	118.7
	4.3	26.23	51.63	0.14	48.22	2.85	0.25	86.0	118.8
	4.4	26.87	52.90	0.13	48.27	2.63	0.25	88.2	118.9
	4.5	27.52	54.17	0.12	48.31	2.43	0.25	90.3	119.0
	4.6	28.17	55.44	0.11	48.36	2.24	0.26	92.4	119.0
	4.7	28.69	56.47	0.10	48.39	2.10	0.26	94.1	119.1
	4.8	29.34	57.75	0.09	48.42	1.94	0.26	96.3	119.2

Figure 9. The top portion of the Data Summary. The data for Figures 3 and 4 are taken from this table.